Combustion in Small-Scale Central-Porous-Media Liquid Film Combustors

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1 Introduction

The demand for personal power systems has been growing owing to the rapidly increasing performance expectations for electronic devices and accessories. Many novel and innovative miniature combustors or reaction devices have been proposed [1-3]. A major challenge for all miniature combustion concepts is the increasing surface-to-volume ratio (S/V) as size decreases. Since it is generally desirable to keep wall temperatures fairly low due to material considerations, a high S/V usually increases the relative heat losses and other wall effects that can quench the combustion process or reduce ignition reliability. These considerations have led researchers to quench-resistant fuels such as hydrogen, or liquid-fuel-film combustors [4], high-preheat concepts (as with the Swiss-roll burner), or catalytic surfaces [3]. Nevertheless, most emphasis was placed on small-scale gaseous fuel combustors during the past decade. Liquid hydrocarbon fuel, however, has inherent advantages of high volume specific power and energy compared to gaseous hydrocarbon fuel. In addition, when considering fuel storage as part of the system mass, heat release from liquid hydrocarbon fuels through combustion remains the highest power density mechanism practically achievable for personal power generation. Although liquid hydrocarbon fueled systems have the potential for high specific energy and power, it is difficult to directly operate combustors on liquid fuels without any heat source for evaporating the liquid fuel in meso-scale systems. Often, utilizing a pilot hydrogen or gaseous hydrocarbon to assist liquid fuel combustion is necessary. Furthermore, flame stabilization in combustors of reduced sizes is sensitive to ambient environment or combustion conditions. Therefore, some combination of flame stabilizer and liquid fuel vaporizer becomes imperative in meso-scale combustion devices. This paper describes the use of a porous metal cap for accomplishing this dual role. Delivering fuel through a central porous metal cap preheats the liquid fuel and acts as a flame holder. Emphasis is focused on describing the flame structure and combustion phenomena in the miniature scale combustion chamber via chemiluminescence and temperature measurement.

2 Experiments

2-1 Concept and Configuration of the Miniature Film Combustor

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High surface-to-volume ratio can be problematic for small-scale combustors since this leads to high heat losses and possible quenching of the flame. In addition, if the burner operates on liquid hydrocarbon fuels, then the high vaporization rates are necessary to sustain the combustion process. Therefore, if the fuel can be injected in a manner that provides large fuel surface area, then the necessary vaporization rates can be maintained. Figure 1 is a schematic of the porous cap combustor where the liquid fuel is pumped through the cap along with some of the combustion air to distribute the fuel along the cap. In this manner, sufficient fuel can be provided as a liquid film covering the porous surface. Because the porous cap is metal, it also conducts heat to assist in directly vaporizing the liquid film from the surface. Swirling air entering a cylindrical chamber serves to draw the liquid fuel through the porous material and generate the liquid film on the surface. The swirling air also provides a recirculation mechanism whereby the flame can be stabilized. Hence, the porous cap has two functions: supplying a liquid-film-surface area large enough to produce necessary fuel vaporization rates and anchoring the flame in the chamber as a flame holder.

Liquid fuel vaporizes from the surface of the porous cap, wherein the liquid fuel is supplied. Evaporation of the liquid fuel and preheating of the fuel vapor on or inside the porous cap requires latent heat and sensible heat, which are supported by convective heat transfer from solid to liquid/vapor via solid-liquid/vapor interactions and by thermal radiation absorption through the liquid fuel and fuel vapor. Chemical reaction takes place outside the porous cap, where the preheated liquid fuel vapor meets and mixes with the swirling air to form a homogeneous gas mixture followed by combustion. Thermal radiation and convective heat transfer from the flame to the porous cap provides the energy for fuel evaporation.

In the experiment, the combustion chamber is made of a stainless steel tube (or a quartz tube for visualization) of 60 mm in length and 9.5 mm in diameter (see figure 1). Heptane fuel is injected from two inlet ports into the bottom of the chamber using a syringe pump, which provides continuous fuel inlet in c.c.-per-hour scale. Air, metered by an electronic flowmeter, is injected tangentially above the fuel ports. The cone-shaped porous cap is bronze and its bead size is 40 μm with respect to 35.6% porosity. There is permeability only at the perimeter of porous cap, but not across the top. The porous cap separates the fuel and air system, so that all of the liquid fuel passes through the porous media to enter the combustion chamber.

2-2 Combustion in the Miniature Porous Cap Film Combustor

As described above, the porous cap plays an important role in spreading the liquid fuel in a thin film on the cap surface and in vaporizing the liquid fuel by conduction. In the present work, where the material of the porous cap is bronze metal, it has excellent thermal conductivity (64 w/m K), an appropriate specific heat (435 J/kg K), and an accessible emitter property (emissivity=0.55). The bronze porous cap can transfer heat from flames immediately by means of conduction and radiation to help vaporize the liquid fuel. The boiling temperature of liquid heptane is around 100°C, and the temperature of the porous media is the essential factor to maintain stable combustion within the device. Figure 2a shows the flame structure in a stable condition (air flow rate is 1.7 m/sec; liquid fuel flow rate is 10.68 mg/sec), and the total equivalence ratio approaches 1. The flame structure in the chamber exhibits a two-layer combustion. One layer is an inner flame with a shape resembling a corn cob. The other layer is an outer flame, which belongs to the swirling flame sheet. To help determine the location and extent of the two flame layers, chemiluminescence imaging measurements were performed. The concentration of OH*, CH*, and C_2* can be linked (at least qualitatively) with fuel-rich and fuel-lean zones. Specifically, C_2* is a short-lived radical that is a good indicator of highly rich reaction zones while CH* can be found over a broader rich equivalence ratio region. OH* is a longer-lived radical describing the broader zone of reaction rather than just the reactive interface [5]. C_2*, CH* and OH* images (see figure 2b, 2c, 2d) were taken with their respective narrow bandpass filters through a 14-bit intensified CCD camera at wavelengths of 307, 430 and 515 nm, respectively. C_2* radicals are distributed near the axis of symmetry and at the base of the chamber, indicating highly rich zones in these regions. In contrast, OH* concentration is rich near the wall and faint in the centerline of the chamber, revealing fairly lean zones near the wall. Moreover, CH* radicals are extensively congregated whether the regions near the wall and near the axis of symmetry. It confirms that the flame structure is composed of two layer flames in the chamber consisting of a lean and a rich premixed flame wing together with a trailing diffusion flame. All of these flames extend from a single point which anchors at the base of the chamber or at the porous cap. For the moment, the stabilization mechanism of combustion in the miniature combustor is assumed to be a tribrachial flame (see Figure 2e). A diffusion flame burns along the porous cap and forms a small pilot flame on the top of the porous cap. A rich premixed flame (RPF) exists between the wall and the porous media, and a lean premixed flame was flung near the wall via a strong swirling air flow.

As indicated earlier, the temperature on the porous cap influences the flame substantially. Therefore, the porous metal seems to be a media that provides liquid fuel with sufficient energy to overcome the latent heat required to vaporize it. Once the temperature on the porous cap rises up over the boiling temperature of the liquid fuel, the stabilization mechanism would be destroyed. To confirm this fact, Figure 3a shows the temperature of the porous cap versus time. In the stable condition, the porous media temperature is smooth and uniform with occasional fluctuations. The fluctuations were motivated by the high-temperature of the porous cap as it was heated via the flame or heat conduction from the wall. However, an overheated porous medium can cause instability and oscillations in the combustion process. First, the heated metal porous medium enhances vaporization of the liquid fuel until dry out of the fuel film. The excess gaseous heptane due to an overheated hot porous metal will decrease the permeability of the porous medium and clog the liquid fuel supply. The cold liquid fuel will then rush in and flush the hot porous medium causing a pulse back pressure rise in the liquid fuel supply due to rapid vaporization in the previous moment. The flushing process steeply reduces the temperature of the porous cap. In this process (see Fig. 3b), the flame becomes unstable and pulsates back and forth in the chamber. The cycle of dryout and replenishment of the liquid fuel is the principle cause of flame oscillation and instability; the cycle depends on the compromise between liquid fuel flow rate and fuel vaporization rate. Figure 3c presents the flame blow-out in the unstable condition. The temperature on the porous cap overtakes the boiling temperature of heptane, and then the combustion oscillation diverges until the flame blows out. To connect this phenomenon with the flame structure, the diffusion flame (or the pilot flame on the porous cap) represents a simple heat source to the porous cap, and it is relevant to combustion stabilization. Similarly, the material of the porous medium dominates the occurrence of the dryout-and-replenishment cycle of the liquid fuel.

3 Conclusion

Providing a metal-porous medium in a small-scale combustor can result in increasing contact surface and conduction heat transfer for liquid fuel evaporation as well as inhibition of flame quench. In addition, the flame structure in a central porous plug combustor consists of two reaction sheet layers,. Chemiluminescence images from an intensified CCD with different narrow wavelength filters confirmed this structure. The chemiluminescence images indicate the concentration of C_2*, CH* and OH* radicals are distributed in different locations of the chamber. A tribrachial flame appears to form as part of the stable operating mode of this combustor based on preliminary observation.

Within the range of stable airflow rates, steady injection of fuel is necessary to prevent oscillations in the flame. The operation of the combustor's fuel supply depends on a competition between the requirements that large fuel flow rates are necessary to keep the porous medium wet and cool to prevent initiation of flame oscillation and yet excessive fuel flow should be prevented to maintain the liquid fuel film in the operation range. The temperature of the porous cap during combustion indicates that the combustor runs fluently when the porous cap's temperature is below the liquid fuel's boiling temperature. Liquid fuel cools down the porous cap and simultaneously acquires sufficient energy for vaporization. A similar process of simultaneous cooling and evaporation is used in miniature reciprocating engines designed for model airplanes. The implementation of the metal porous injector and swirling air flow create a miniature combustor for complete combustion of liquid fuel. These features help resolve the difficulties associated with short residence time and flame quench that can be issues in small scale combustion systems.

References

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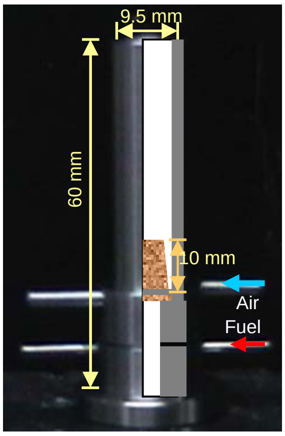

Figure 1. The configuration of miniature combustor

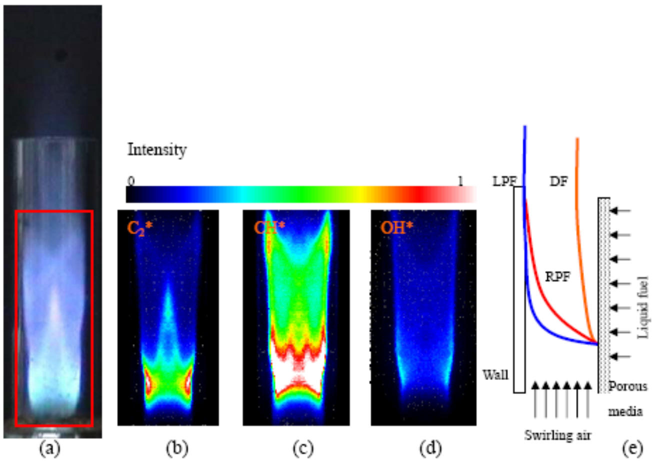

Figure 2.
(a) The flame structure
(b) C_2* image (c) CH* image (d) OH* image
(e) Schematics of tribrachial flame near the porous media (LPF, lean premixed flame; RPF, rich premixed flame; DF, diffusion flame)

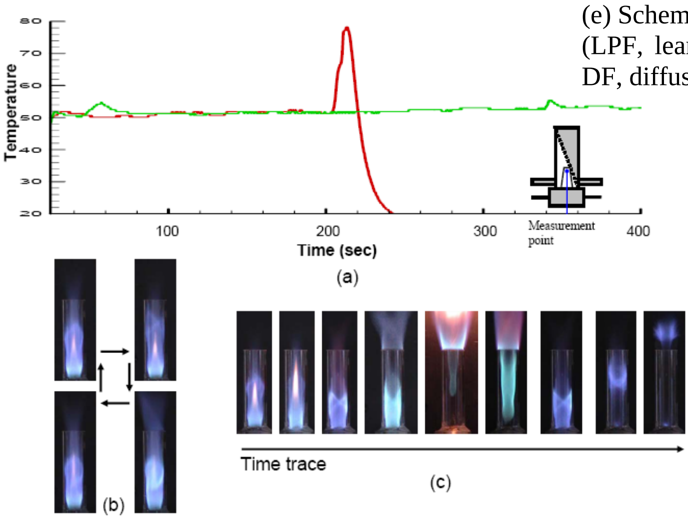

Figure 3.
(a) Temperature on the porous cap
(Red is unstable case; Green is stable case)
(b) Combustion oscillation in stable condition
(c) Flame blow-out in unstable condition